Baryon Acoustic Oscillations (BAO) at LBNL

David Schlegel

1. What are BAO? How do they measure dark energy?

2. Status of current experiments using the Sloan Digital Sky Survey (SDSS)

3. BOSS proposal for precision BAO experiment (after SDSS)

4. Next Generation upgrades: automated fiber spectrographs with >1000 fibers

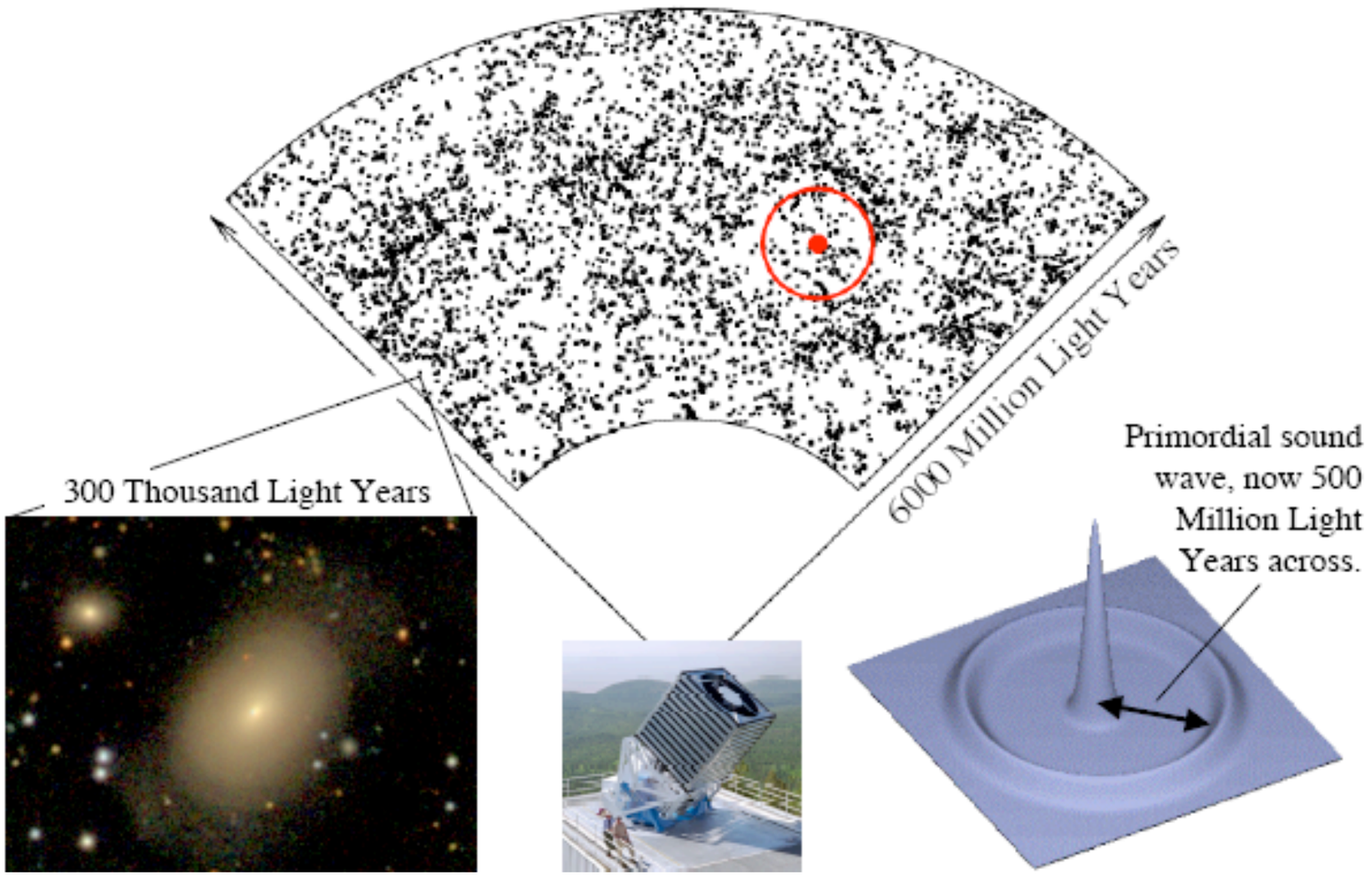
Baryon Acoustic Oscillations (BAO)

our newest tool...

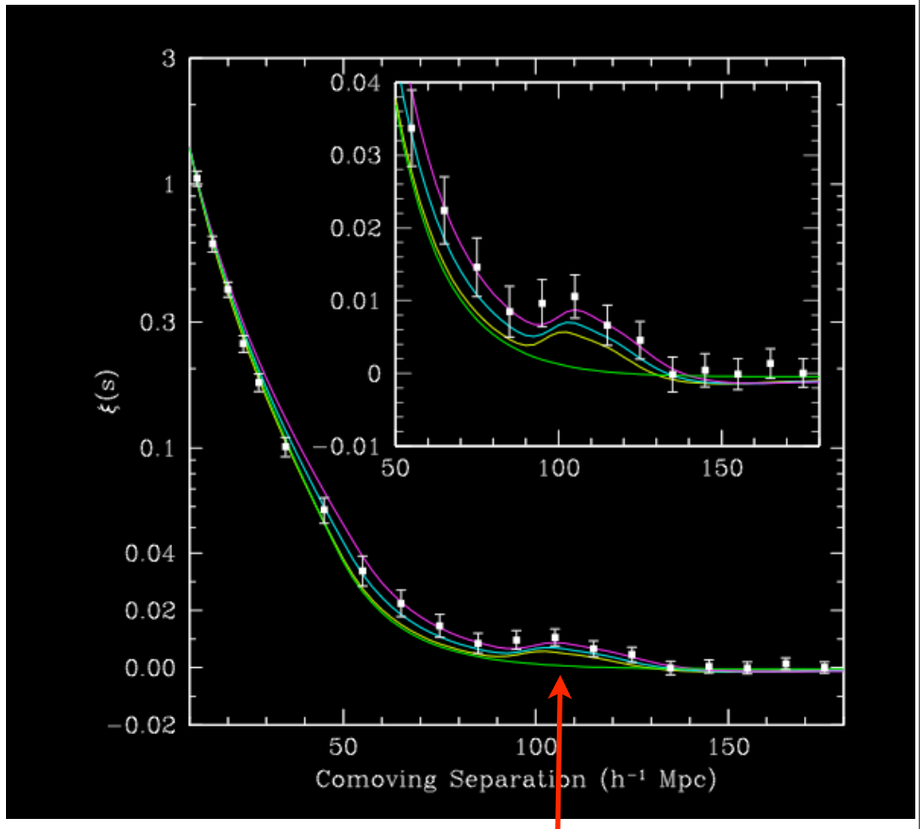
Motivation: BAO is one of the 4 dark energy experimental techniques

- Supernovae -- ***standard candle***, 1st results in 1998
- BAO -- ***standard ruler***, 1st results in 2005
- Weak lensing
- Cluster counts

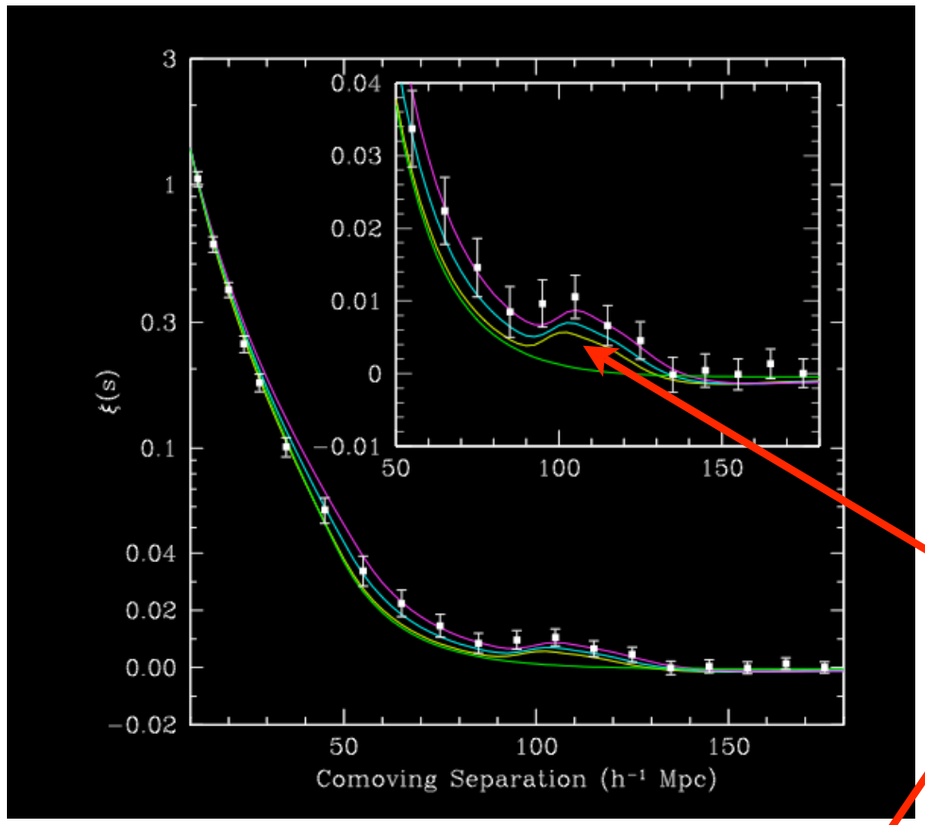
1st results from SDSS 3-D galaxy survey



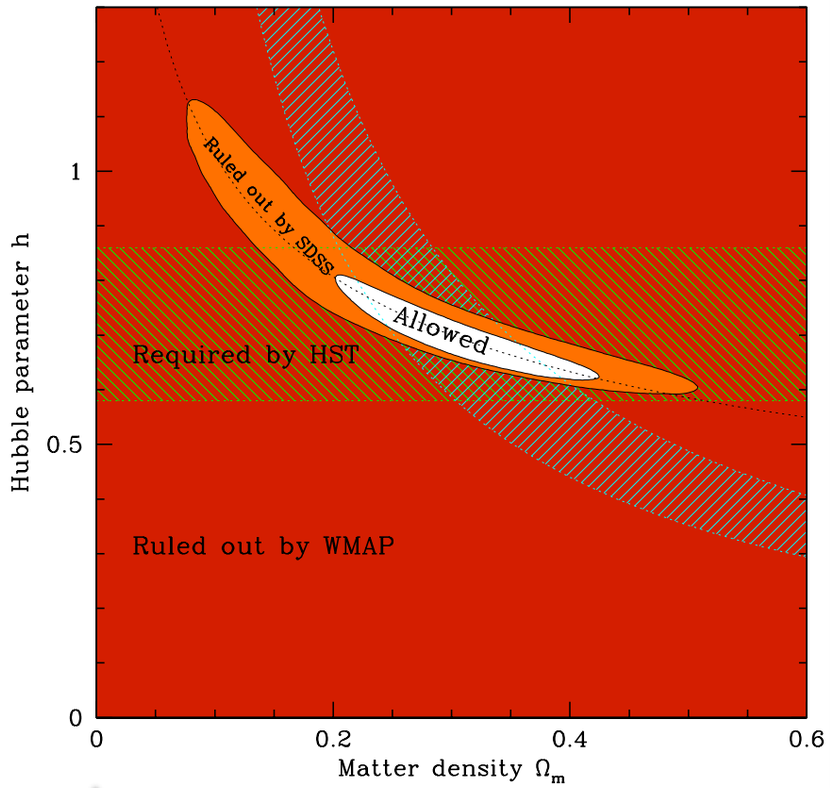
Eisenstein et al. 2005
SDSS spectro-z
40,000 red galaxies
$0.15 < z < 0.40$



Baryon acoustic oscillations: First Results

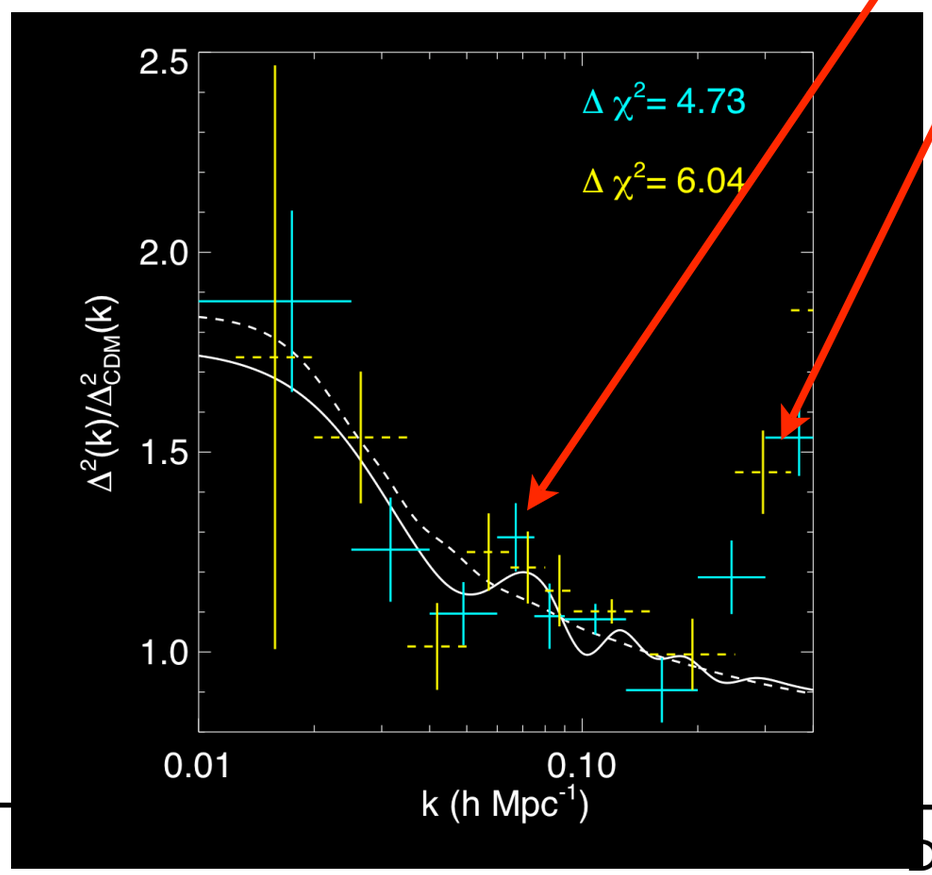


Eisenstein et al. 2005
SDSS spectro-z
40,000 red galaxies
0.15 < z < 0.40
3.5-sigma detection
(configuration-space analysis)

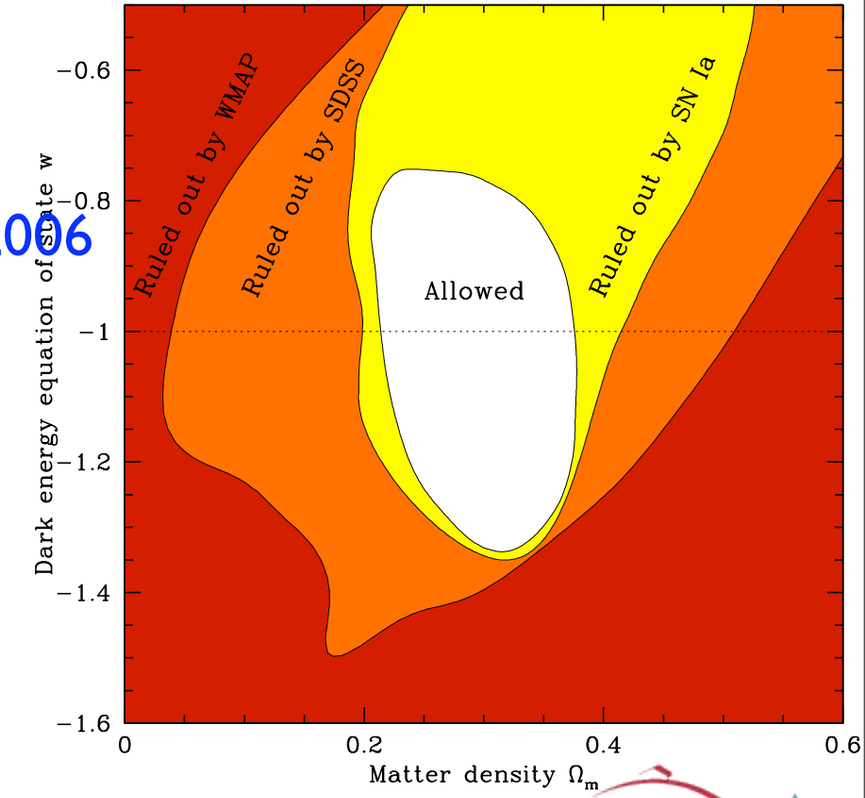


baryon acoustic peak

non-linear growth of structure



Padmanabhan,Schlegel et al. 2006
SDSS photo-z (less accurate)
600,000 red galaxies
0.15 < z < 0.60
2.5-sigma detection
(power spectrum analysis)



Next-Generation BAO Experiment: BOSS (Baryon Oscillation Spectoscopic Survey)

A variety of facilities considered for next-gen BAO experiment:
Lick 3-m, Keck 10-m, MMT 6.5-m, ...

SDSS telescope secured for next-gen BAO experiment:
July 2006: Competitive proposal to use (upgraded) SDSS telescope for next-gen BAO
Nov 2006: BOSS proposal selected (from 7) for all dark+grey time for 5 of 6 years
Nov 2006: First BOSS collaboration meeting
Feb 2007: DOE R&D proposal for upgrading SDSS spectroscopic system
P.I. David Schlegel & Natalie Roe
Subcontracting with Chicago, JHU, NYU, Princeton, UC Santa Cruz, U Washington
2007: Funding requests expected to Sloan Foundation, NSF, and DOE
2009-2014: BOSS spectroscopic survey

The future

LBNL+NERSC involvement:
David Schlegel, P.I.
Natalie Roe, Steering Committee member (forming collaboration)
co-I's: Bob Cahn (Senior Staff), Peter Nugent (NERSC),
Nikhil Padmanabhan (Hubble/Chamberlain Fellow), Nao Suzuki (postdoc),
Martin White (UCB + Senior Staff)

Proposal submitted to ARC in July 2006

They own the telescope

Strong support from LBL and many other institutions.

Refining the Distance Scale to 1% with the ARC 2.5-m Telescope

David Schlegel[1], Daniel Eisenstein[2], James Annis[3], Neta Bahcall[4], Bruce Bassett[5], Chuck Bennett[6], Michael Blanton[7], Francisco Javier Castander[8], Masataka Fukugita[9], James Gunn[4], Pat Hall[10], Tim Heckman[5], Wayne Hu[13], Zeljko Ivezic[11], Benjamin Koester[12,13], Jill Knapp[4], Guinever Kauffmann[14], Robert Lupton[4], Rachel Mandelbaum[4], Patrick McDonald[15], Robert Nichol[16], Nikhil Padmanabhan[1,4], Saul Perlmutter[1], Gordon Richards[6], Adam Riess[6,17], Natalie Roe[1], Connie Rockosi[18], Roman Scoccimarro[7], David Spergel[4], Michael Strauss[4], Nao Suzuki[1], Alex Szalay[6], Istvan Szapudi[19], Max Tegmark[20], David Weinberg[21], Martin White[1], Simon White[14], Idit Zehavi[22]

[1] *Lawrence Berkeley National Laboratory,* [2] *University of Arizona,* [3] *Fermi National Accelerator Laboratory,* [4] *Princeton University,* [5] *University of Cape Town,* [6] *Johns Hopkins University,* [7] *New York University,* [8] *Institut d'Estudis Espacials de Catalunya,* [9] *University of Tokyo,* [10] *York University,* [11] *University of Washington,* [12] *University of Michigan,* [13] *University of Chicago,* [14] *Max Planck Institut für Astrophysik,* [15] *Canadian Institute for Theoretical Astrophysics,* [16] *University of Portsmouth,* [17] *Space Telescope Science Institute,* [18] *University of California at Santa Cruz,* [19] *University of Hawaii,* [20] *Massachusetts Institute of Technology,* [21] *The Ohio State University,* [22] *Case Western Reserve University*

ABSTRACT

We propose to use the SDSS facility post-2008 to conduct the largest spectroscopic survey to date of cosmological large-scale structure. The survey is designed to use the baryon acoustic oscillation phenomenon to make significant improvements in our measurements of the cosmic distance scale and hence the acceleration of the expansion rate of the Universe. The primary goal is a survey of Luminous Red Galaxies (LRGs) out to $z \approx 0.7$ over 10,000 square degrees, aimed at the measurement of the baryon acoustic peak in the large-scale galaxy correlations.

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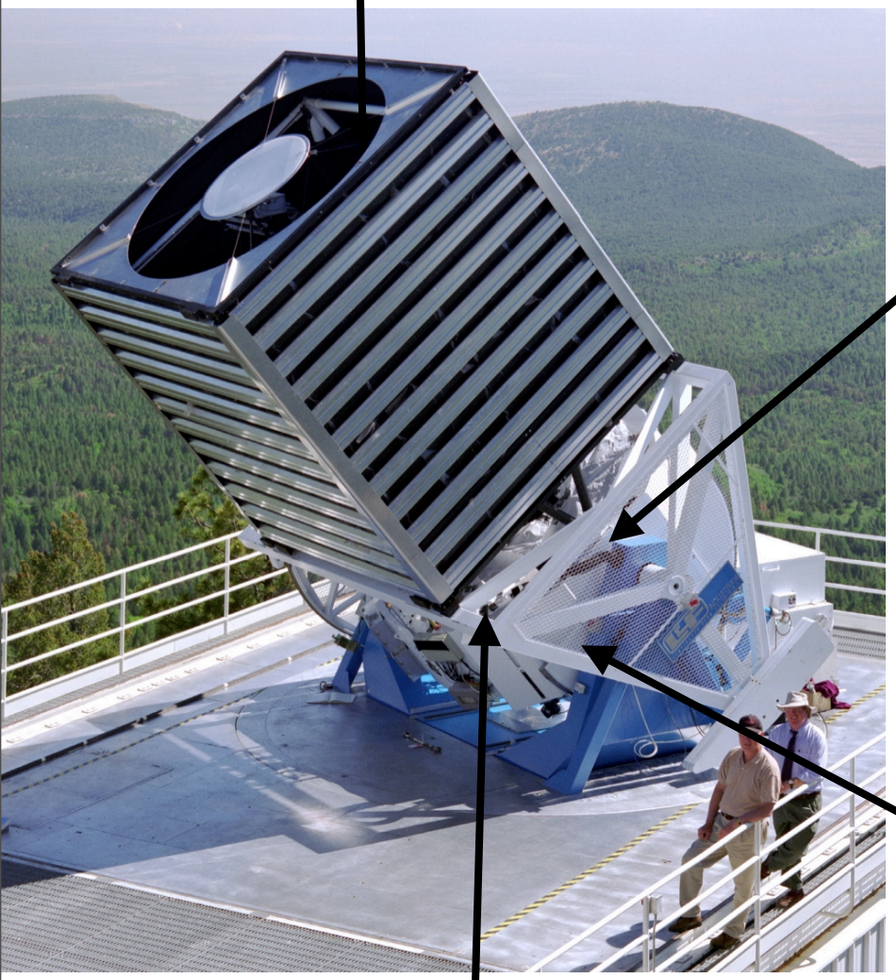
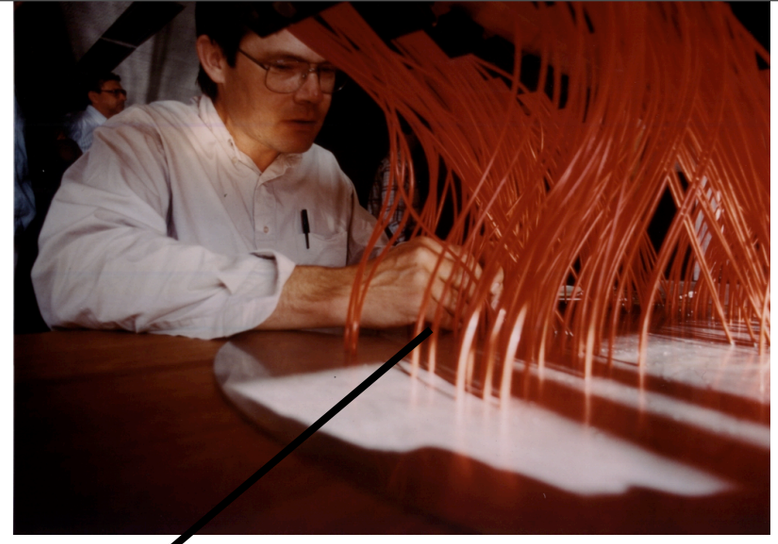
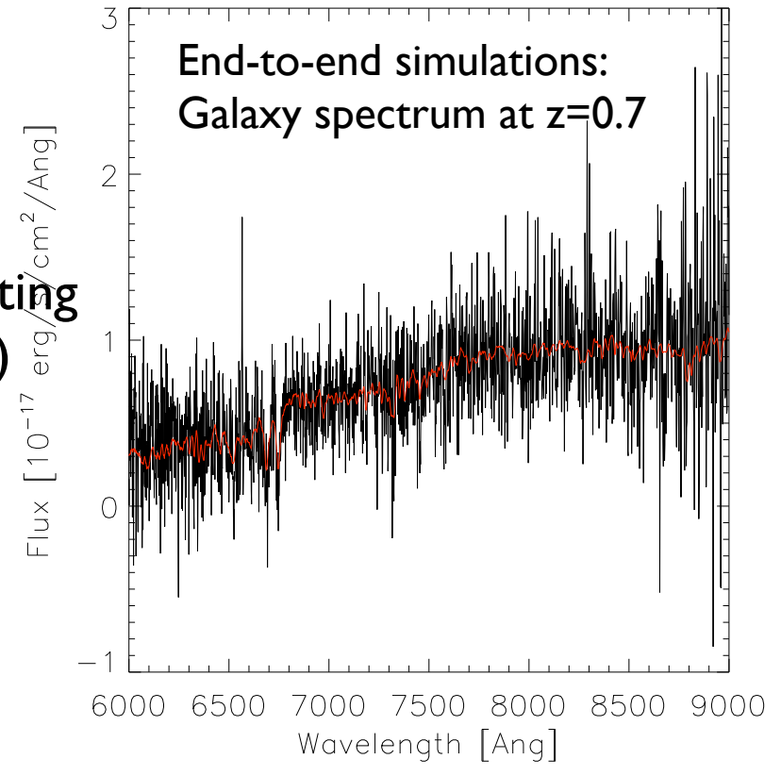
SDSS system upgrades for BOSS

Largest field-of-view of any large telescope -- DONE!



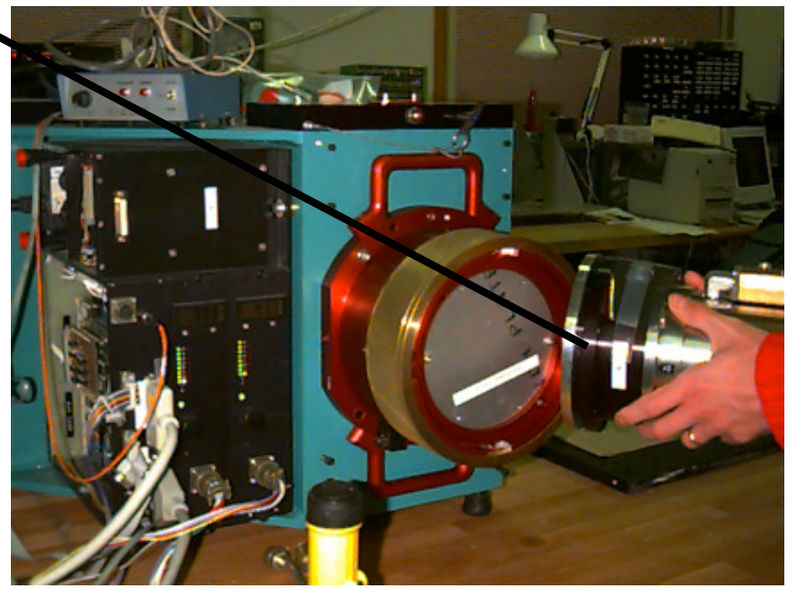


1000 small-core fibers to replace existing (more objects, less sky contamination)



Software development underway at LBL, Princeton, NYU

Swap gratings for VPH



Replace red CCDs w/red-sensitive **LBL/SNAP CCDs**, making it possible to go to higher-z

Replace blue CCDs w/UV-sensitive Fairchild CCDs, making it possible for Lyα at z=2.3→3

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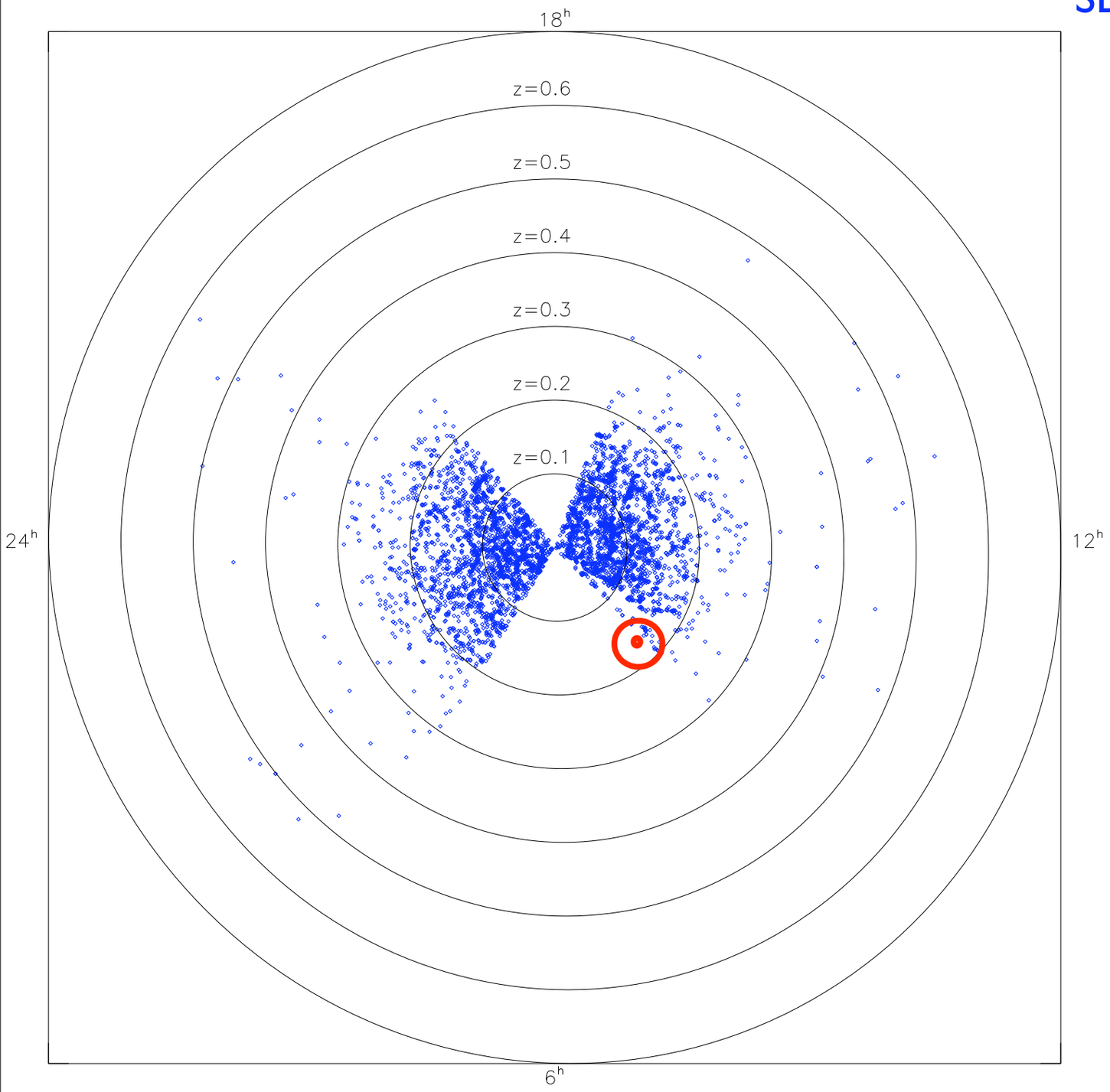
Baryon acoustic oscillations:

The tool is large galaxy redshift surveys.



SDSS main survey (too small!)

Baryon acoustic oscillations:

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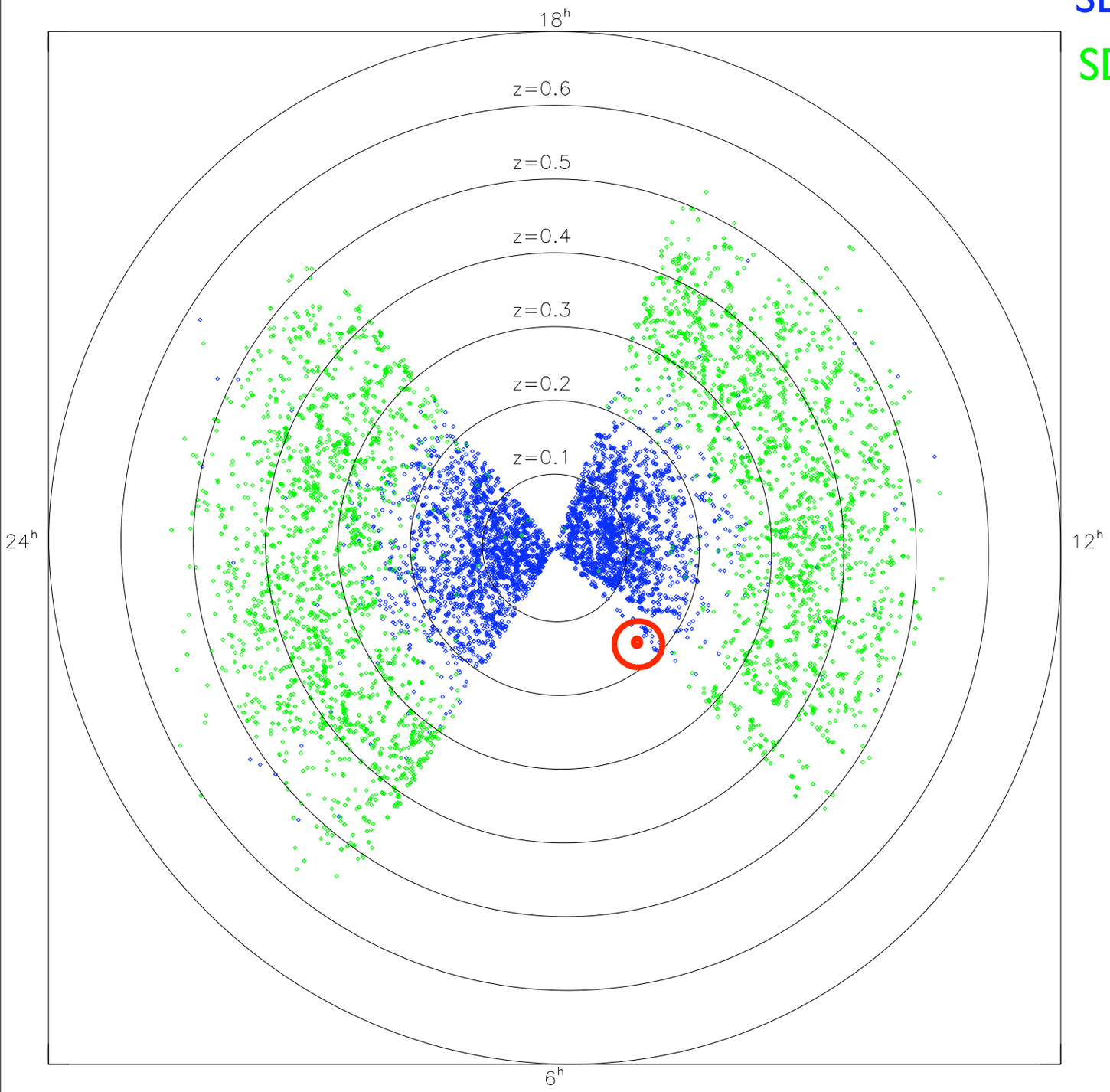

SDSS main survey (too small!)

SDSS + SDSS-II red galaxies
8000 deg^2 (finish in 2008)
samples 10^{-4} galaxies/Mpc^3

Baryon acoustic oscillations:

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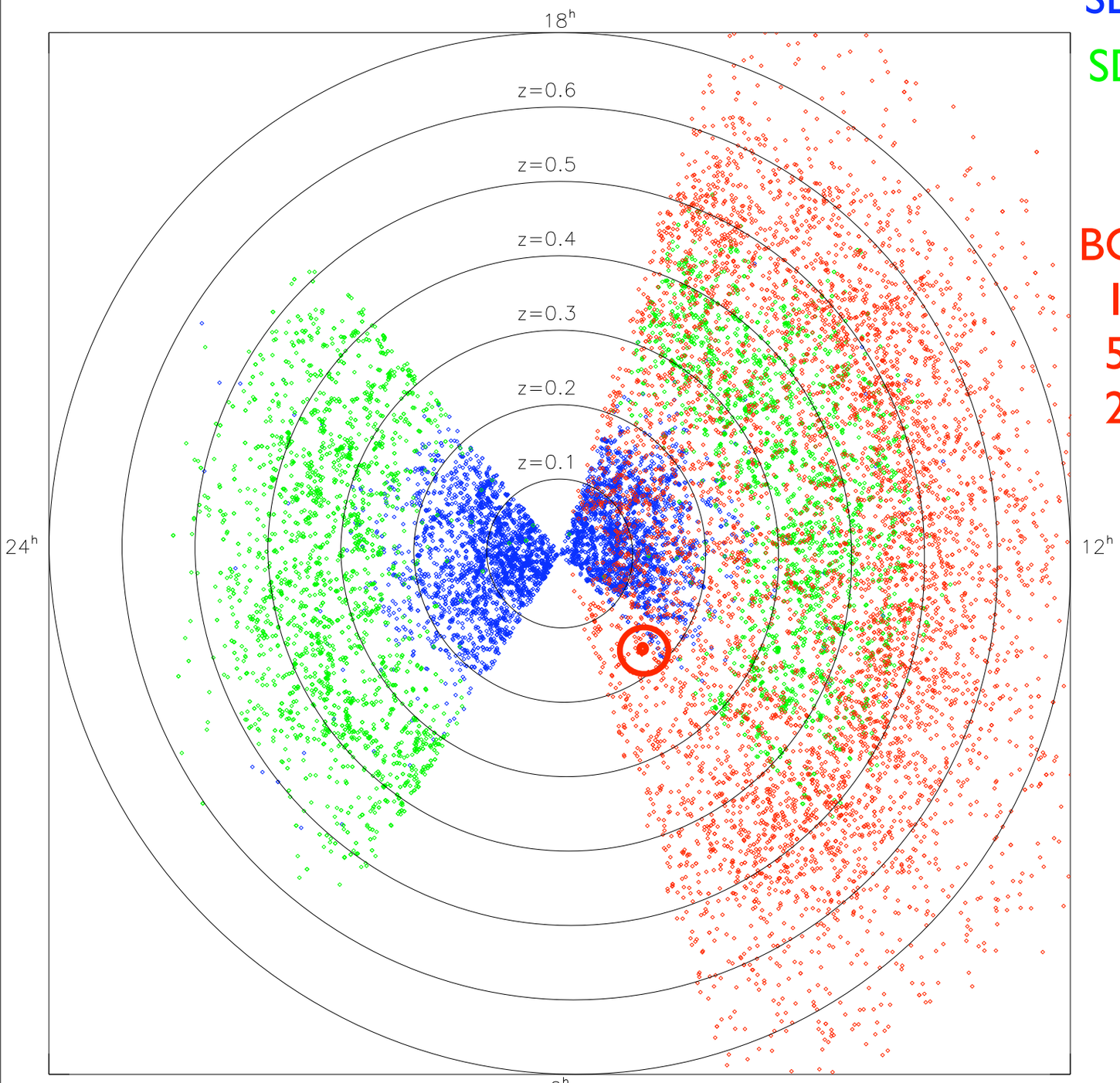
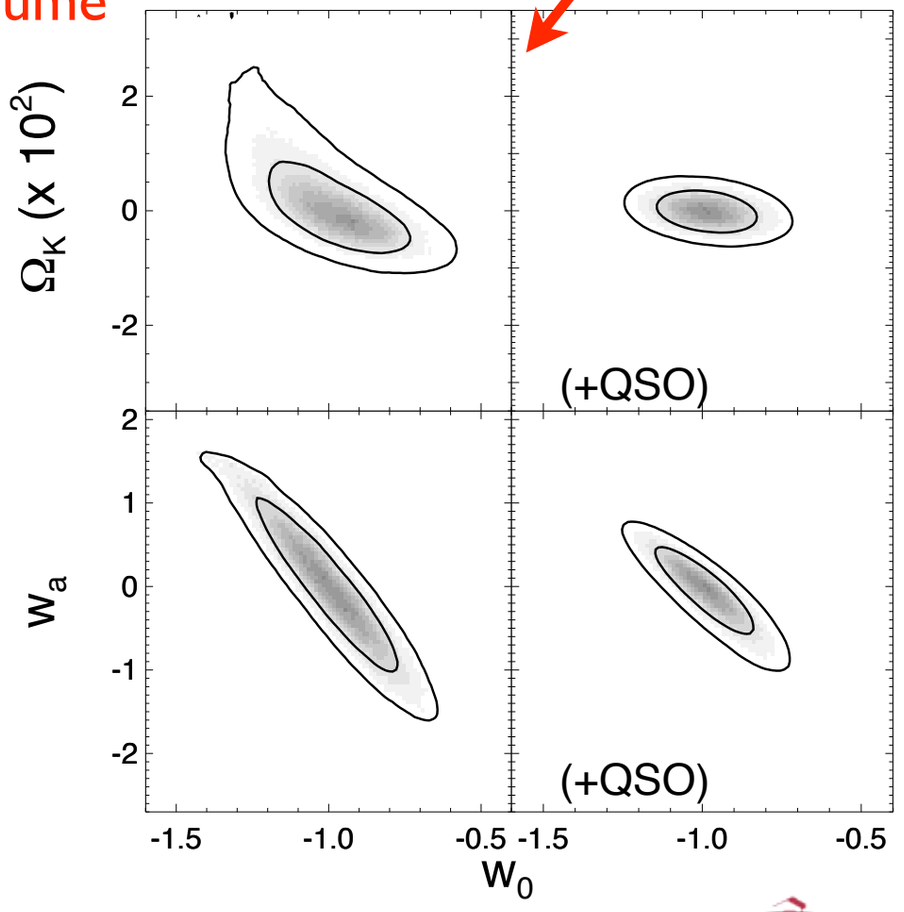


SDSS main survey (too small!)

SDSS + SDSS-II red galaxies
8000 deg^2 (finish in 2008)
samples 10^{-4} galaxies/Mpc^3

BOSS red galaxies
10,000 deg^2
5x sample density (shot noise)
2x volume

← PROPOSED



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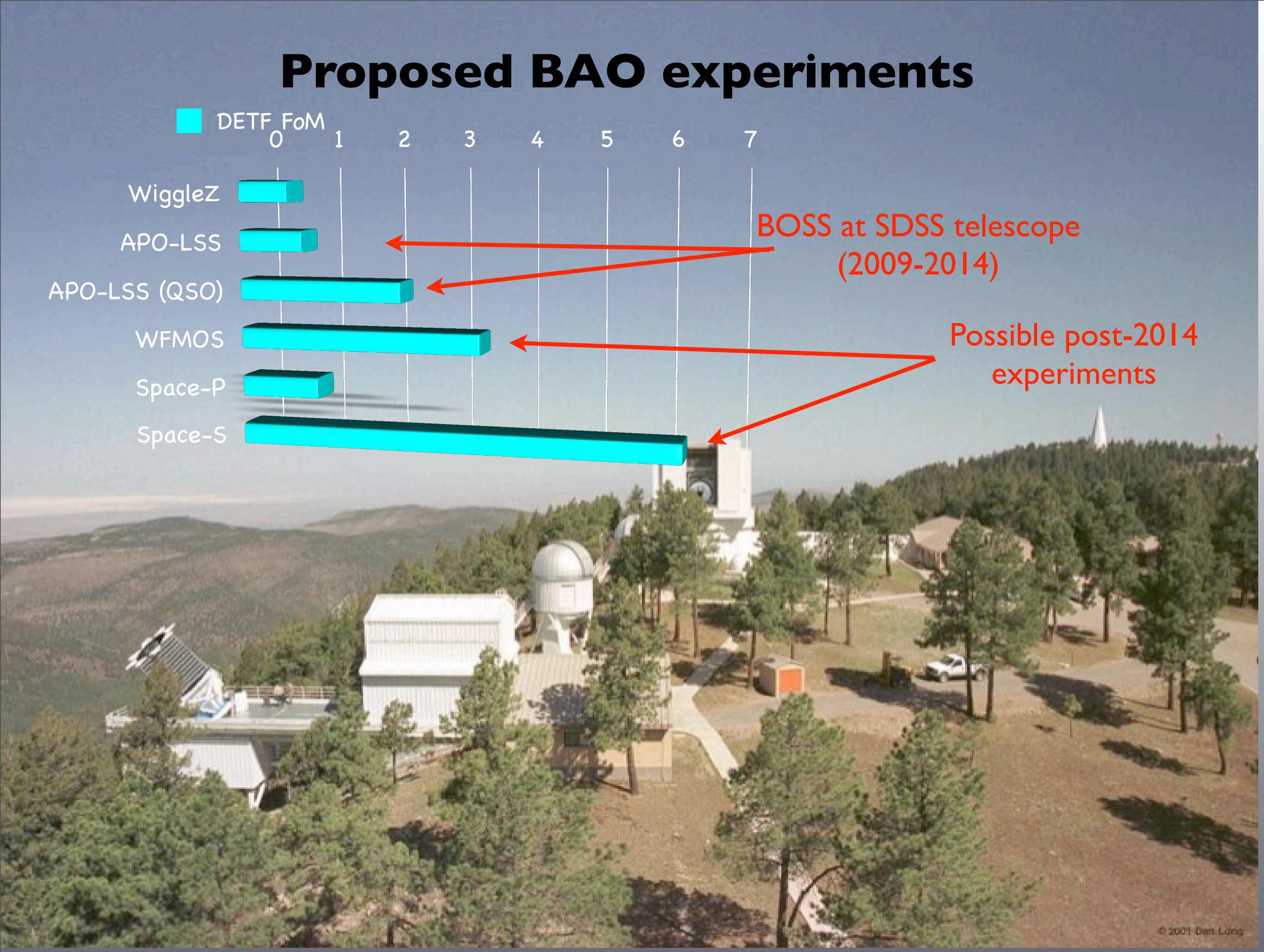
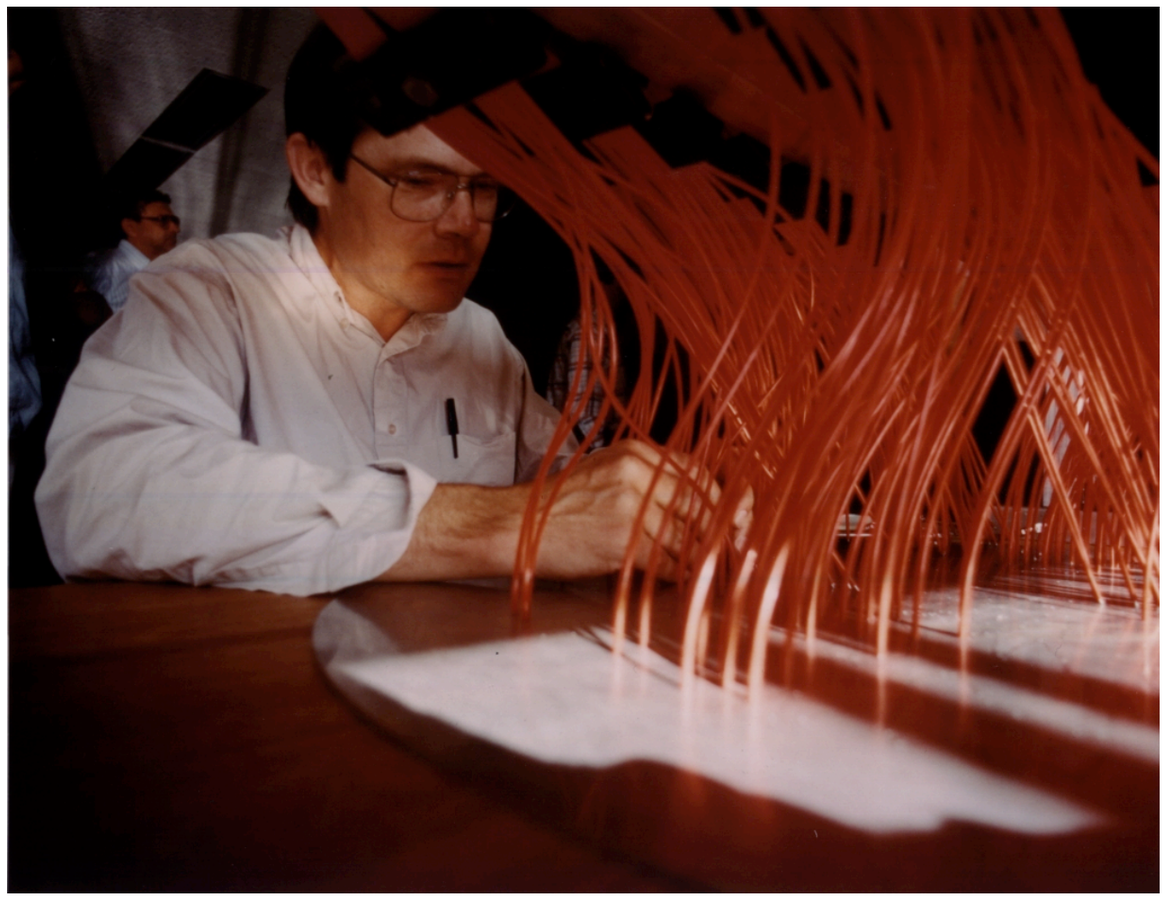
Proposed BAO experiments

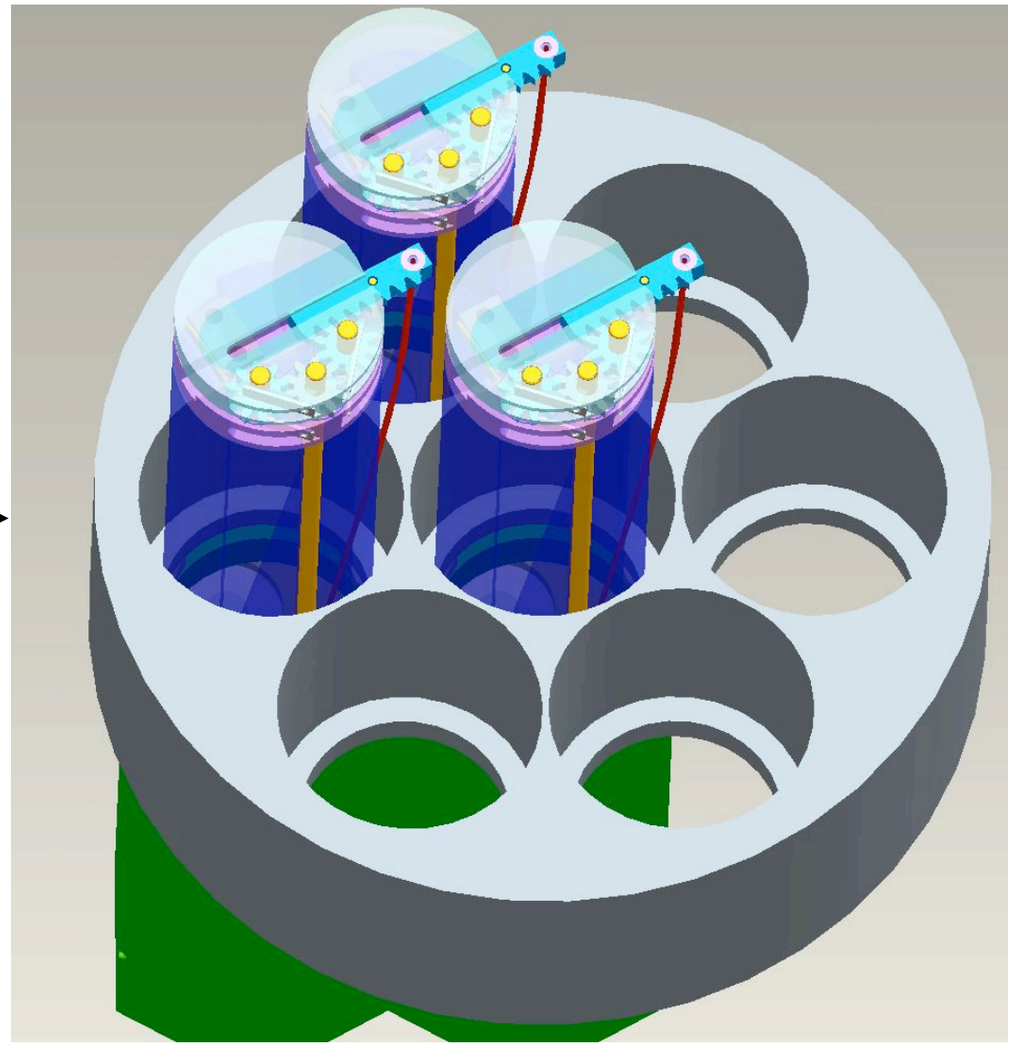


Future BAO Experiments: automated fiber positioner

SDSS hits limit of 2.5-m telescope + old plug-plates "technology"
Future systems will require larger telescopes (Keck 10-m, Subaru 8-m, Spanish GTC 10.4-m)
+ automated fiber positioning with >1000 fibers
Huge demand for such technology for ground-based dark energy experiments:
baryon acoustic oscillations, redshifts for weak lensing, kinetic S-Z, ...
Difficult to fund such R&D at Universities ➡ Funded by LBNL LDRD



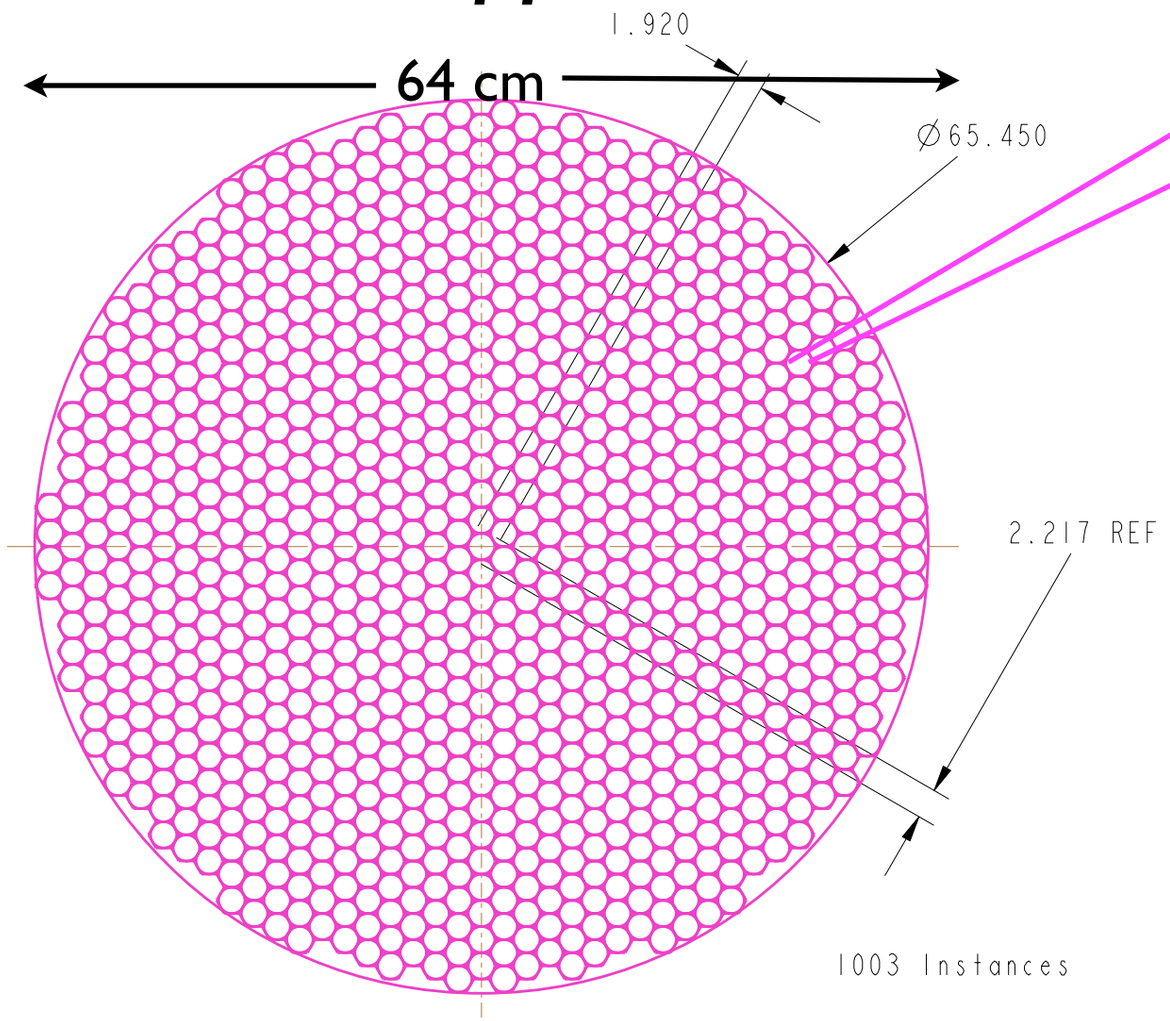
SDSS Director Rich Kron plugging 640 fibers in ~1 hour

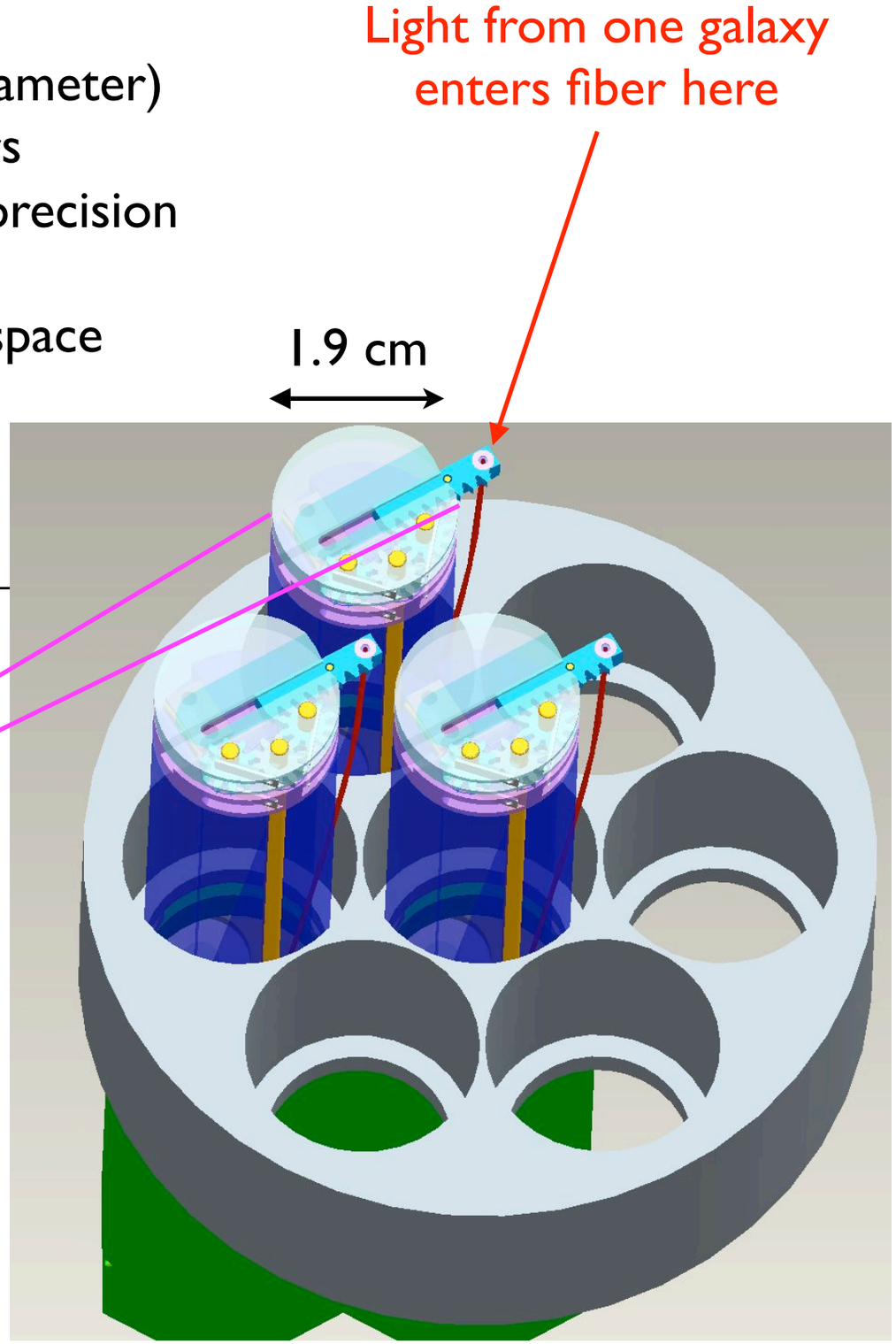


LBNL automated fiber positioner concept:
Scales to any # of fibers

LBNL fiber actuator concept

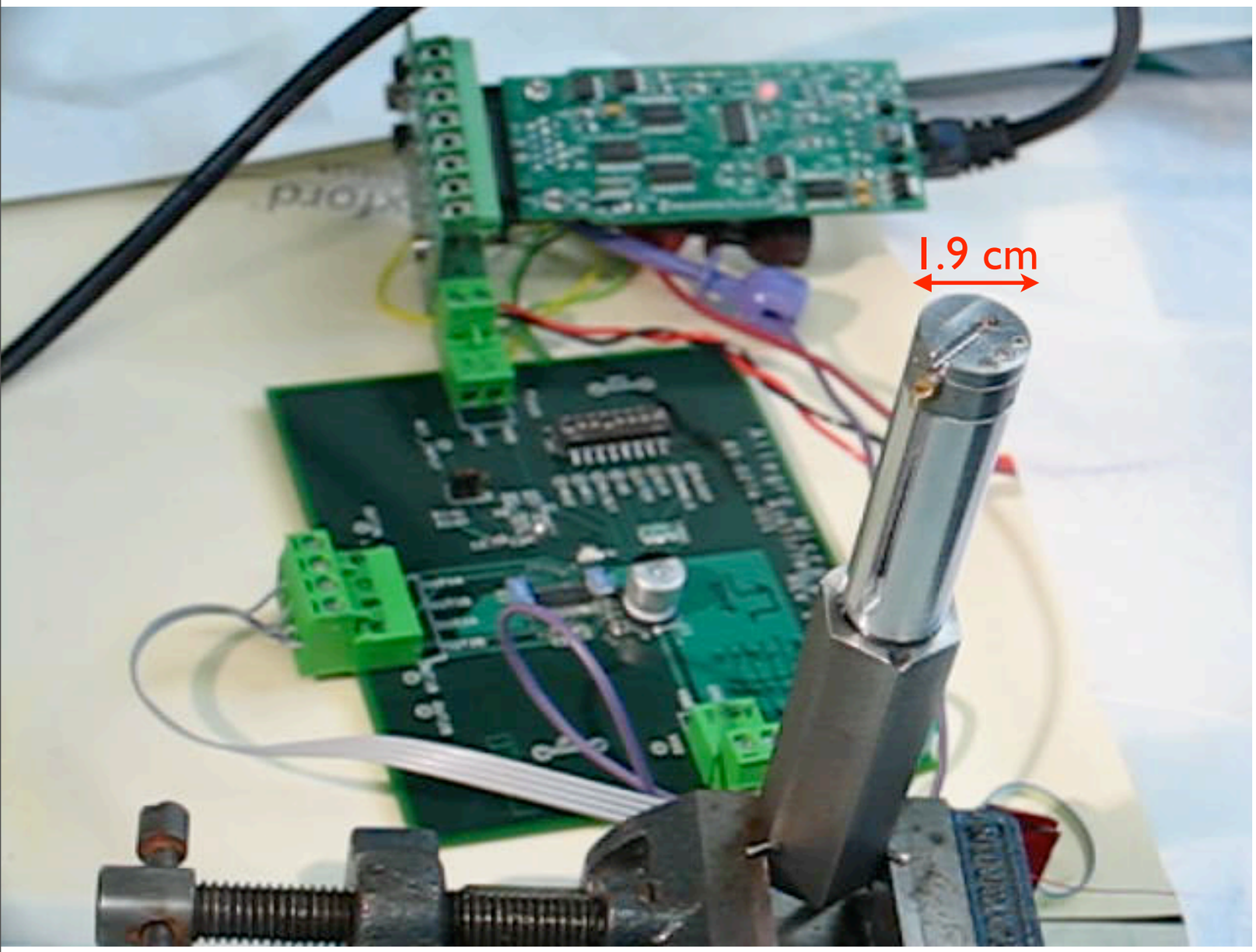
Divide telescope focal plane into 1000 hex cells (64 cm diameter)
Each fiber is ***individually actuated*** with 2 Swiss motors
Local accuracy is only 1 part in 1000 for 20 micron precision
Center-to-center spacing = 1.9 cm
Fiber reach extends slightly to adjacent cells ➡ No dead space
Reconfiguration time < 1 min
Run open loop (no feedback)
Target cost: $1000 / fiber
No limit to number of fibers!

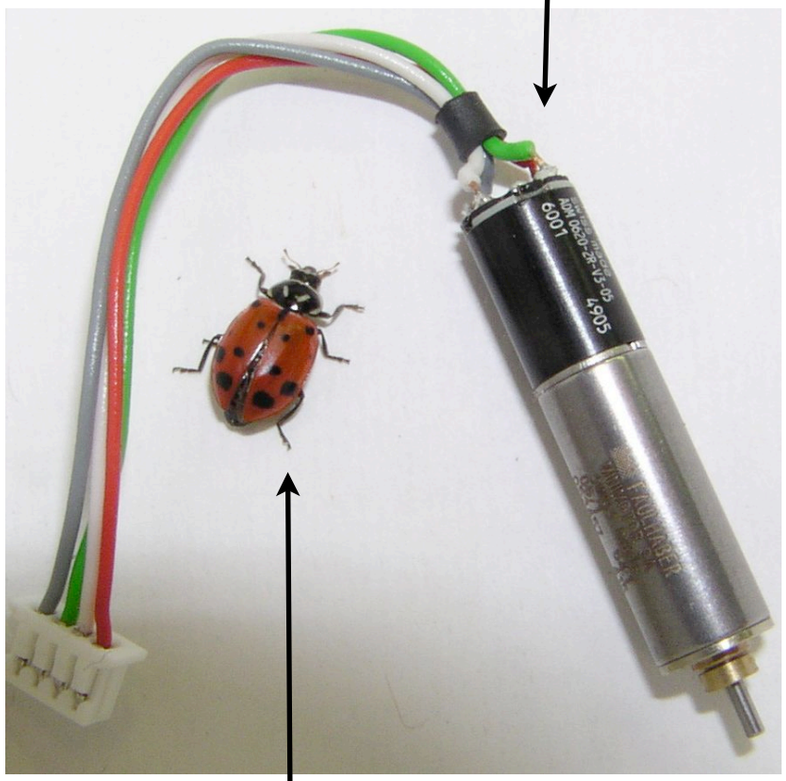




LBNL fiber actuator prototype!

All components complete for rotational (θ) stage, not quite for r-stage
Control electronics bread-boarded (will be miniaturized)





Baryon Acoustic Oscillations (BAO) at LBNL
Conclusions

- Baryon acoustic oscillations are a rapidly maturing method for measuring the cosmological distance scale and dark energy.
  - Highly robust. Trigonometric method. Errors dominated by sample variance.
  - Complementary to supernova cosmology

- BOSS (on SDSS telescope) will be the definitive low-redshift data point, reaching near the cosmic variance limit.
  - Dedicated BAO experiment 2009-2014
  - Data would also be the best available for large-scale structure, e.g. P(k).
  - Possible measurement at z=2.5 from QSOs (speculative)

- The future?
  - R&D on fiber-positioning technology for big telescopes:
    Push BAO to higher redshifts z>0.7
    Enabling technology for dark energy from weak lensing maps
  - What is the systematics floor on d_A? 1% ? 0.1% ?
    Large computation problem! Requires >5 Gpc^3 simulations
  - Study ground-based vs. space-based experiments?

Extra Slides

Recent related publications

- *Photometric Calibration of the Sloan Digital Sky Survey Imaging Data, ApJ, 2007,* Padmanabhan, Schlegel, et al. (submitted)
- *The Clustering of Photometric Luminous Red Galaxies in the Sloan Digital Sky Survey*, MNRAS 2007, Padmanabhan, Schlegel, et al.
- *Simulations of Baryon Oscillations,* Astropart Phys 2006, Huff, Schulz, White, Schlegel, Warren
- *Correlating the CMB with luminous red galaxies: The integrated Sachs-Wolfe effect*, Phys Rev D 2006, Padmanabhan, Hirata, Seljak, Schlegel, et al.
- *Going nonlinear with Dark Energy Cosmologies,* Phys Rev D 2005, Linder & White
- *Calibrating photometric redshifts of luminous red galaxies*, MNRAS 2005, Padmanabhan, Schlegel, et al
- *Baryon Oscillations*, Astropart Phys 2005, White
- *Cross-correlation of CMB with large-scale structure: Weak gravitational lensing*, Phys Rev D 2004, Hirata, Padmanabhan, Seljak, Schlegel, Brinkmann
- *Sloan Digital Sky Survey Imaging of Low Galactic Latitude Fields: Technical Summary and Data Release*, AJ 2004, Finkbeiner, Padmanabhan, Schlegel, et al.
- *SDSS data management and photometric quality assessment*, AN 2004, Ivezic, Lupton, Schlegel et al.

BAO experiments: How well do we do?

- Fisher matrix calculation gives distance errors, using only acoustic oscillation information, ignore broad band power. (see Seo and Eisenstein 2007)
- MCMC to get cosmological parameters
- Priors :
  - 1% low-z SN distances (eg. SNLS), z=0.05, 0.15, 0.25, 0.35
  - 5% prior on SN magnitude (well calibrated by low-z BAO)
  - 2% prior on $\Omega_m h^2$, fix d_{LS}/s
  - Allow h, dark energy, curvature to vary
- Figure of Merit = Inverse area of 95% contour

Current + proposed BAO experiments

SDSS & SDSS-II	ARC 2.5-m, 3° FOV	640 fibers	2000-2008	8000 deg^2	<z>=0.35
AGES (Eisenstein)	MMT 6.5-m, 1° FOV	300 fibers	2005-...	(small)	
BOSS LRGs	ARC 2.5-m, 3° FOV	1000 fibers	2008-2014	10,000 deg^2	<z>=0.7
BOSS QSOs	ARC 2.5-m, 3° FOV	1000 fibers	2008-2014	5,000 deg^2	<z>=2.5
LAMOST	Chinese 6-m, 2° FOV	4000 fibers	???	???	<z>=0.7
AAOmega LRG	AAT 4-m, 2° FOV	400 fibers	Rejected		
AAOmega WiggleZ	AAT 4-m, 2° FOV	400 fibers	2006-... (200 nights)	1,000 deg^2	<z>=0.8
HETDEX	Hobby Eberly 11-m	200 IFUs	???	200 deg^2	z=1.8→3.8???
FMOS	Subaru 8.4-m, 0.5° FOV	200 fibers	2007-... (200 nights)	200 deg^2	<z>=1.4
WFMOS (previously KAOS)	Subaru 8.4-m, 1° FOV	~3000 fibers	2014? (120 nights)	1000 deg^2	<z>=1
WFMOS (previously KAOS)	Subaru 8.4-m, 1° FOV	~3000 fibers	2014? (60 nights)	150 deg^2	<z>=3
ADEPT (JDEM proposal)	Earth orbit 1.3-m	Grism 1→2μm	2014?	30,000 deg^2	z=1→2
Cosmic Inflation Probe	L2 orbit 1.8-m, 0.3° FOV	Grism 2.5→5μm	???	140 deg^2	z=3→6.5

5.9

1.8

6.0

?

Next-generation

Next-next-gen

Figure of merit from Dark Energy Task Force

(White & Padmanabhan, priv com)

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